Sanitary Ventilation*

W. F. WELLS, F.A.P.H.A.

Associate Professor of Research in Airborne Infection, University of Pennsylvania School of Medicine, Philadelphia, Pa.

FIFTEEN years ago we demonstrated before a joint meeting of these sections an apparatus for the study of the bacterial behavior of air [1]; at the meeting ten years ago we described a method for the measurement of sanitary ventilation [2]; five years ago we discussed air disinfection in day schools [3]; this paper considers the sanitary significance of ventilation. Paradoxically, the hygienic interest in ventilation waned with rise of sanitation. Before the patterns of spread of ingested infection and inhaled contagion were clearly differentiated, the sanitary disproof of the miasmic origin of enteric infection discouraged further belief in air-borne respiratory contagion; transfer of contagious disease then was ascribed to personal contact.

Even in the most congested districts of our largest cities, contact infection was of secondary consideration in the environmental control of typhoid fever. The gradual decline in residual typhoid resulting from elimination of carriers created by water-borne infection came as a minor and unpredicted bonus, compared to the reduced rates immediately following an investment in pure water.[4] In the control of contagious epidemics on the other hand, such as measles, for instance, or influenza, where a single case can initiate a contagious chain of growing generations of infection, quarantine has until recently been the only environmental means available. Whereas the relatively static dissemination of infection in space dominates spread of typhoid fever and other water-borne intestinal infections, the propagation of air-borne respiratory contagion in time is intrinsically dynamic.

DYNAMICS OF CONTAGION

The autocatalytic nature of contagion has been expressed mathematically for theoretical epidemics in homogeneous aggregations homogeneously exposed. "Almost all workers in the analytical theory of epidemics assume that the rate at which an infection passes in a population is proportional jointly to the product of the number of persons I who are infectious and the number of persons S who are susceptible to the infection. This is called the law of mass action. Thus, if the rate of new infections be C the law is written as $C = rIS$, where r is a constant,"[5] r then being the effective contact rate. This elementary equation approximately describes the dynamic pattern of intra-aggregational spread of contagion.

EFFECTIVE CONTACT RATE

In the study of contact infection, measles has played a leading role and is suggested as a natural index for study of the dynamics of droplet nuclei contagion. The value of S in the above formula is directly indicated; persons

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are assumed to be susceptible before, and immune after, having measles. Also, the value of I is generally ascertainable; direct exposure to a previous case the second week before symptoms appear can usually be detected; younger children normally contract the disease when exposed in the home.

In a quantitative study of effective contact the suburban primary school offers decided advantages: children ordinarily enter school before having measles but contract this disease before graduation; in school they are homogeneously exposed within standard classrooms; both exposure and effective contact can be established through attendance records.

By such means the effective contact rate r of measles in classrooms of three suburban primary schools during the past four years has been evaluated.[6] Among approximately 791 susceptible classmates of pupils who became ill with measles while attending classes (a unit of exposure), 87 contracted the disease after a normal incubation period. An effective contact rate of 11.0 per cent is consistent with unproductive exposures observed in schools[7] and should theoretically yield in the formula some indication of productive exposures in classrooms meeting with Pennsylvania code requirements of ventilation.

INTRAGROUP CONTAGION

As compared with 80 or 90 per cent secondary attack rate among primary school children in families reported by Chapin,[8] an effective contact rate of 10 per cent in classes may seem unimpressive, but this represents merely the static infection in a single generation. Most of the infected pupils attend class until symptoms appear, and by reëxposing their class become the infectors

THRESHOLD SANITARY VENTILATION

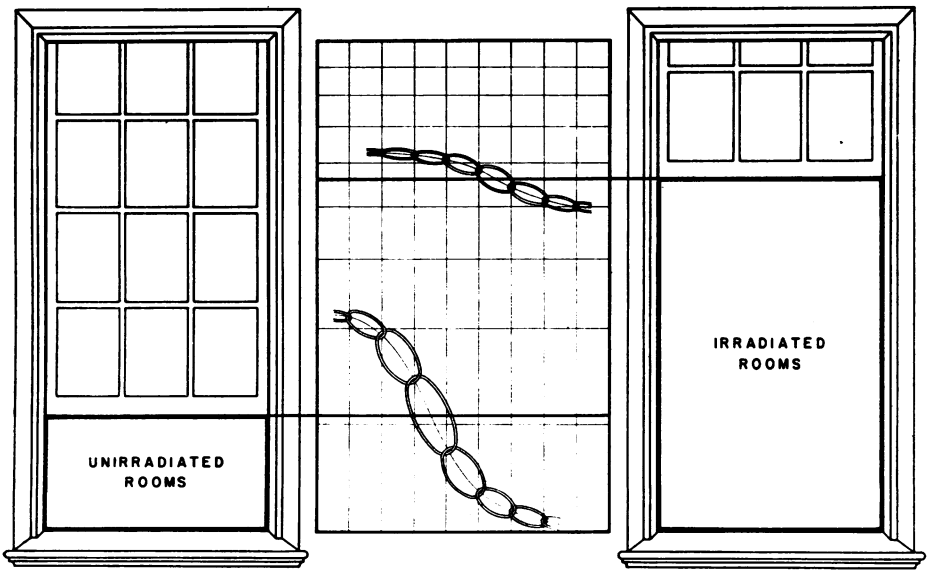

CHART I—Diagram Relating Sanitary Ventilation to Air-borne Contagion

Area inside each link of chains of generations of infection in irradiated and unirradiated schools during 1941 epidemic corresponds to percentage of susceptible pupils infected in that generation period, i.e., week and half. Center of largest link indicates number of susceptible pupils sharing ventilation at peak of epidemic when generations begin to decline, thus locating threshold sanitary ventilation per susceptible pupil. Chart on which chains are constructed described in Dynamics of Air-Borne Infection, *Am. J. M. Sc.*, 206:11–17 (July), 1943.

of a second generation. This linkage of cases in one generation to infectors of the next forges the chains of successive generations illustrated on Chart 1.

Obviously while cases exceed infectors rS is greater than unity and generations are growing, reach a "steady state" at the peak of the epidemic when $rS_T = 1$, and decline when infectors exceed cases, or rS falls below unity. The "density" of susceptible persons, S_T, at the epidemic peak, or the reciprocal of the effective contact rate, is called the "threshold," because if this "density" is not maintained by accession of persons susceptible to the disease, as when contagion becomes endemic, cases are sporadic and the disease dies out. During an epidemic the "density" theoretically falls as far below as it started above the "threshold," though our school results seem to indicate a proportional rather than an absolute relationship.[9]

To one accustomed to the erratic behavior of measles in classes such an orderly array may seem unrealistic, yet the diagonal on Chart 2, approximating the computed total infections for classes of differing susceptibility, portrays diagrammatically the pregnant fact that the percentage of susceptible pupils who contract the disease when introduced into classes increases with the number of susceptible children in the classrooms. The reality of this fact is indicated by the percentage of susceptible pupils in different grades of a large centralized school near Syracuse who contracted measles during a recent epidemic.[10] With enrolled classes of 33 pupils (an approximate average) the numbers plotted on the chart correspond with percentages of susceptible children in the grades. Since the cases contracted outside the classroom are included in these data, the plotted number of cases per 100 susceptible children exceeds somewhat the number resulting only from dynamic spread of measles within the classroom. Nevertheless it becomes evident that "crowding" is a major factor in the contagiousness of measles.

SANITARY VENTILATION

Now in terms of droplet nuclei infection, S is proportional to the amount of infected air breathed by susceptible persons; I to the amount of infection contributed to the air by the previous generation of cases; and r to the dilution of infection afforded by ventilation, or to the reciprocal of VS, where V represents ventilation per susceptible occupant (Chart 1). The substitution of these factors has proved the basic equation of the law of mass action to apply in quantitative experimental air-

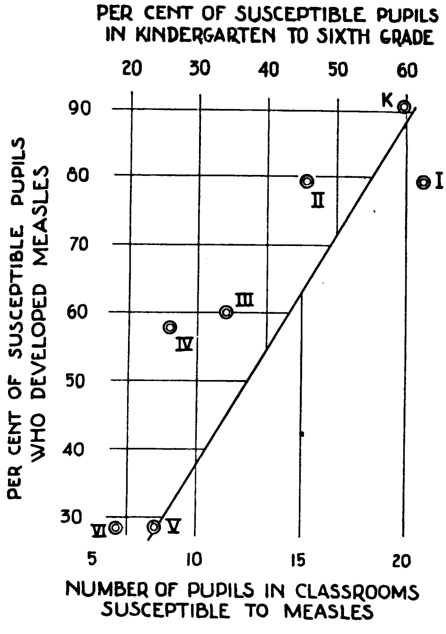

CHART 2—Increasing Percentage of Susceptible Pupils Who Develop Measles as Number of Susceptible Pupils per Classroom Increases

Diagonal approximates percentage computed with 10 per cent effective contact rate per generation. Marked circles indicate percentage of susceptible pupils in primary grades of Mexico School who developed measles in 1946 epidemic (10). Percentage of susceptible pupils corresponds to 33 pupils per class (approximate average).

borne tuberculosis in rabbits.[11] Since rS_T becomes unity at "threshold density of susceptibles," ventilation per susceptible occupant at this "density," V_T, becomes the natural sanitary unit of ventilation and the law of mass action, as applied to air-borne contagion, then becomes $CV = IV_T$. Only below threshold ventilation, or when V is less than V_T, can droplet nuclei contagion become epidemic; cases are sporadic when V exceeds V_T, and the infection dies out.

Ventilation is usually expressed as cubic feet of fresh air replacement, or cubic feet per occupant—per susceptible occupant in sanitary ventilation. Sometimes it is more convenient to express ventilation in air changes of confined atmospheres, and if a *lethe* of disinfection is defined as the bactericidal equivalent of bacterial removal by dilution with one air change (one volume pure air replacement with continuous mixing), sanitary ventilation by air disinfection can be expressed in cubic foot-lethes.[12] By principles underlying these transformations elaborated elsewhere,[2] sanitary ventilation can be measured bacteriologically by the equilibrium concentration of standard test organisms, atomized at a constant rate into an enclosed atmosphere at representative locations, determined at another representative location with and without air disinfection. Multiplying the die-away rate without disinfection by the ratio of equilibrium concentrations gives *lethes*, or equivalent air changes.

Radiant disinfection of air in primary schools has played a dominant role in the experimental study of sanitary ventilation. The number of air-suspended bacteria killed by irradiation of a dry confined atmosphere can theoretically be deduced from a generalized hypothesis combining three accepted laws: the inverse square law of radiant intensity; the Roscoe-Bunsen law of reciprocity of time and identity of exposure; and the quantum (logarithmic) law of disinfection.[13] By this hypothesis the number killed becomes proportional to the number of photons, or to ergs of radiant energy intercepted by living bacteria. If a ray be regarded as a constant stream of photons, then the number of photons in a confined atmosphere is proportional to the total lengths of the rays between the points of entrance and disappearance from the enclosed space. Dividing the volume of the room into this total length, or the sum of the products of the rays into their length, gives average intensity. Thus, radiation in watts multiplied by average ray length in feet gives total irradiation in foot-watts which, divided by room volume in cubic feet gives average intensity in watts per square foot.

This reciprocal relationship between radiant flux and distance traversed through an enclosed space is obvious with uniform light intensity. Thus, one watt of uniform parallel light, such as sunlight, traversing 10 feet of a transparent column 10 feet long and of 1 square foot cross-section, will irradiate 10 cubic feet to 10 foot-watts, or 1 foot-watt per cubic foot, giving an intensity of 1 watt per square foot. In like manner, 10 watts falling perpendicularly upon 10 square feet of a side, passing through 1 foot of this column, will also irradiate 10 cubic feet of air to 10 foot-watts, giving average intensity of 1 watt per square foot. In any position or in any form, 10 cubic feet would be irradiated by 10 foot-watts, the product of the flux into mean ray length. Regardless of the form of the space or the direction of the rays, irradiation is given by radiant flux multiplied by mean ray length.[14]

It follows from the generalized law of radiant disinfection that the greatest number of organisms suspended in a given volume of air are killed when uniformly exposed to a given amount of irradiation, the lethal efficiency of uniform irradiation therefore being a maximum. We were unable to irradiate large spaces uniformly but were able to devise a chamber providing uniform exposure to a point source at the center, toward which air flowed with a velocity inversely proportional to the square of the distance from the source. The product of time and intensity of exposure of air-borne organisms to the source was therefore constant at any point, and the determined foot-lethes divided by computed foot-watt minutes of exposure, or the product of average intensity by time of exposure, gave the lethal equivalent of irradiation. Against standard bacterial suspension in dry air 0.002 foot-watt minutes of irradiation in the 2537Å wave band was equivalent to a cubic foot-lethe, less than a tenth of the irradiation required in humid air, on moist agar surfaces, or in aqueous suspension.[15] If radiation in this wave band be adopted as standard lethal radiation, then a foot-watt minute of standard uniform lethal irradiation is equivalent to 500 cubic foot-lethes of standard air disinfection, or cubic feet of sanitary ventilation.

But it is not feasible to irradiate the occupied zone of a room to the desired average intensity; and, so, irradiation efficiency in practice depends upon design. Generally the amount of irradiation realized from a radiant source in an enclosed space depends directly upon mean ray length; the uniformity of irradiation of the space normally increases with mean ray length, the uniformity of exposure depending upon air circulation usually increases as rays are lengthened; and the disinfection of organisms en route from occupant to occupant approaches average disinfection as rays are lengthened. The hygienic rating of disinfection thus increases *inter alia* with mean ray length.[13]

The role of air circulation in equalizing exposure of air-borne organisms to differing intensity in ventilated spaces is little appreciated by those who have not measured radiant disinfection by bacteriologic procedures. With good design, air circulation between the occupied and upper irradiated zone, expressed in terms of the amount of recirculation of the air through a chamber uniformly irradiated with the given number of foot-watts exceeded three air changes per minute. Thus, by radiant disinfection with 6 foot-watts per pupil, more than twenty times the sanitary equivalent of standard school ventilation—exceeding threshold sanitary ventilation (Chart 1)—has been attained in experimental schools.[16]

DYNAMIC EXPERIMENT

Measles epidemics would not propagate in these schools according to the dynamic hypothesis discussed above. Records [17,16,4,6]* of nine years' experience in the irradiated Primary Department of the Germantown Friends School and six in the two Swarthmore Primary Schools, as compared with four years' experience in the unirradiated Primary Department of the William Penn Charter School and the two Nether Providence Primary Schools, indicate that:

1. The effective contact rate of measles in classrooms was reduced; per hundred susceptible classmates of a pupil becoming ill with measles while attending class (unit of exposure) 11.0 contracted the disease in unirradiated schools, during the second following week, as against 3.1 in irradiated schools.
2. The dynamic spread of the measles in the school was checked; per hundred susceptible pupils of unirradiated schools more than twice, and in classrooms more than five times, as many were infected.
3. The community threshold for primary school children was raised; per hundred pupils in unirradiated primary schools, half again as many had had measles.

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* Note: presented on slides at the meeting but omitted on editorial grounds.

SANITARY SURVEY

It seems theoretically possible to control epidemics of air-borne contagion by covering dynamic foci with threshold sanitary ventilation; these foci constitute the primary sources of contagious epidemics in the community. Any attempt to tabulate the relative importance of various atmospheres encountered in experimental studies discloses a lack of trustworthy information on the essential channels of commerce in contagion. Nevertheless, in experimental design and the interpretation of epidemiological data, the relative insignificance of unblockaded channels is tacitly assumed.

Before designing a municipal water supply, the static factors which govern spread of intestinal infection, amount of pollution (I), size of aggregation (S), and effective dilution (r), must be surveyed. Control of static factors which determine effective contact rate and exposure time is not enough to prevent contagious epidemics by sanitary ventilation; dynamic factors which determine intra-aggregational reëxposure linkage of generations, and the hazard of inter-aggregational linkage of exposure within the community, i.e., the chance of introduction of infection to and dispersion from social groups, must also be evaluated. A sanitary survey of the various atmospheres breathed by aggregations under observation is required to evaluate methods of control of air-borne infection. Sanitary discrimination in the dynamic control of air-borne contagion is even more essential than in the static control of water- or milk-borne infection.

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